Outlook for development of a scintielectron detector with improved energy resolution

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Abstract

The development prospects have been considered of a scintillator-photodiode type detector with improved energy resolution attaining several per cent ($R = 1 - 2\%$). The main contributions to the scintielectron detector energy resolution have been analyzed theoretically and their theoretical and physical limits determined. Experimental data have been presented on properties of scintillators of promise confirming the possibilities to minimize each of the resolution components. New ways are proposed to optimize the detector statistical contribution and the scintillator intrinsic resolution. A special role of the latter is outlined as the critical factor for the spectrometric possibilities (threshold) of scintillation-photodiode type detector with improved energy resolution at energy values E_γ from *662 keV* to *10 MeV*.

Key words: scintillator-photodiode detector, energy resolution, intrinsic resolution.

Solid state detectors of scintillator-PMT (S-PMT) and scintillator-photodiode (S-PD) types are used widely along with semiconductor ones (SCD). In the latter type, the ionizing radiation is converted immediately into charge carriers while in scintielectron S-PMT and S-PD ones, a two-stage conversion takes place: first into optical photons (in the scintillator) and then into charge carriers (in the photoreceiver). The two-stage conversion causes energy losses and redistribution (dissipation), thus, in the case of small-volume detectors, the SCD sensitivity and energy resolution are one decimal order higher. An S-PD detector comprising a traditional CsJ(TI) scintillator of about $1sm^3$ volume and a silicon or HgI2 photodiode has the energy resolution 5 to *6%* at room temperature for *662 keV* line [1, 2].

While the energy conversion in scintillators has been considered comprehensively enough and several models have been proposed to date describing that process satisfactorily [3-6], there are no works considering possible correlation between integral characteristics of that process (quantum efficiency, conversion one, self-absorption, etc.) and energy resolution of the scintillator itself and of the scintillator-containing detection system as a whole; the same is true for theoretical consideration of the limiting energy resolution as a function of the scintillator parameters. This work is dedicated to theoretical consideration of that problem.

Let the energy resolution of a scintillator-photodiode combination be considered. Under Gaussian approximation of the electron signal output shape, the resolution R is expressed as

$$R = \frac{FWHM}{MAX} = G\frac{\Delta E}{\overline{E}}\,, \tag{1}$$

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where $G = 2\sqrt{2\ln 2} \approx 2.36$; $\overline{E}$ – the average energy; $DE \equiv (\Delta E)^2 = \overline{E^2} - \overline{E}^2$ – the spectral line dispersion. The dependence on the ionizing radiation energy E is defined by the conversion efficiency of the system, η_p, in the peak corresponding to the photo-absorption in the scintillator:

$$E = \eta_P E_\gamma; \quad \overline{E} = \overline{\eta}_P E_\gamma; \quad \Delta E = \Delta E(E_\gamma; \overline{\eta}_P, D\eta_P; \dots)\,. \tag{2}$$

Strictly speaking, the physical conversion efficiencies of the system, the total one η_{PD} (the energy yield of electrons per $1MeV$ of ionizing radiation) and the scintillation one η_{sc} (the absolute light yield per $1MeV$), and thus the peak one rip η_p (the fraction of the total efficiency corresponding to the photo-absorption peak of the spectral couple S-PD), are fluctuating being depended not only on the ionizing radiation energy but also on a multitude of physical and geometric parameters denoted in (2) as $(\dots)$. That is why the broadening ΔE (and thus the detector resolution) depends non-monotonously on its conversion efficiency $R = R(\eta)$, measured under the current regime. Nevertheless, it follows from experiments that correlations associated with the light yield improvement remain conserved and result mainly in an improved resolution R, in particular, in high-uniform materials containing no activator.

Mathematically, the non-monotonous dependence $\Delta E = \Delta E(\eta)$ is due to that the main parameters of Gaussian distribution, the mean value and dispersion, are explicitly independent from each other. The spectral line broadening is due not only to statistical contributions reflecting the relations of the detector resolution R with its conversion efficiency η but also to non-statistical fluctuations including those of geometric, dynamic, space-nonuniform competing quantities non-proportional to E_γ which define the detector conversion yield. Under account for the above complication, the most effective way to determine the detector resolution is to discriminate the most important noise channels so that the corresponding fluctuations could be considered as independent ones and then to estimate each of those. The independent fluctuations are added vectorially and result in the following expression for the resolution (a α is the noise channel number)

$$R^2 = \sum_\alpha R_\alpha^2. \tag{3}$$

It is quite natural to define the resolution of a scintielectron detector (as well as in [8])

$$R^2 = R_{sc}^2 + R_{st}^2 + R_{pd}^2\,, \tag{4}$$

where R_{sc} is the scintillator intrinsic resolution; R_{st}, statistical fluctuations of the energy carriers (photons and electrons); R_{pd},the noises of photodiode and electronic devices. Note that each of each contribution in (4) may in turn include partial components answering to specific broadening mechanisms. Since $R_\alpha < R$, it is necessary to provide a noise level of 1 to 2% for each component to attain an improved R value of the same order.

First let conditions be determined allowing to neglect the photodiode noise R_{pd}. This contribution depends on the total number of noising electrons, N_{noise} related to the useful electron signal, N:

$$R_{noise} \sim \frac{N_{noise}}{N} = \frac{(\delta E)_{PD}}{\eta E_\gamma}\,, \tag{5}$$

where $(\delta E)_{PD}$ is the corresponding energy spread; η is meant to be the average value unless otherwise noted. It will be shown in what follows that a rather high efficiency of $\eta \sim 10\%$ is necessary to compensate the detector statistical noise. From Eq. (5), we obtain that, the average energy being $E_\gamma = 0.6$ to $1MeV$ and the useful signal $N > 30000$ electrons, the resolution $R_{pd} < 1 - 2\%$ is believed to be small if $(\delta E)_{PD}$ less then from l to $2keV$ or $N_{noise} \sim (2 \div 3)10^2$ (electrons). Such a low noise level is already attained in modern semiconductor photodiodes. For example, the silicon photodiode used as a SCD has a resolution of *5.5 keV* for *122 keV* line of ^{57}Co and records reliably *5.5 keV* from ^{55}Fe [9]. Thus, its resolution (expressed in relative units) for ^{137}Cs line must be about $R_{pd} \sim G(5.5keV/122keV) \sim 0.8\%$, i.e. less than *1%*. In the high-energy spectrometry the photodiode noise is even lower, since $N \sim E_\gamma$, in Eq. (5).

The statistical component R_{st}, includes independent contributions from quantum fluctuations of the number (or energy) of scintillation photons $R_{st,sc}$ and the photodiode photoelectrons $R_{st,ph}$ thus,

$$R^2_{ST} = R^2_{st,ph} + R^2_{st,el}\,. \tag{6}$$

In contrast to the cascade theory of statistic fluctuations in a scintillator-photomultiplier block [10], the statistical fluctuations of photons cannot be neglected in this case. In high-resolution scintielectron detectors, a nearly ideal energy transfer from the scintillation quanta to the photodiode electrons, therefore, their statistical contributions are of the same order of magnitude. Note that the $R_{st,ph}$ is often neglected also in S-PD detectors, but only at resolutions not less than 4 to 5%.

Let a formula for R_{st} be derived in a system with high conversion efficiency. Let us consider the conversion of a y quantum energy into a scintillation photon and then into an electronic signal as independent events in a Bernoulli check sequence. The statistical fluctuations of such a check series are described by binomial distribution [11] with the average value $x = Np$ and dispersion $Dx = Np(l - p)$ where N is the check number (the number of converted particles at 100% efficiency); p, the event probability η_{sc} and η, respectively). Thus,

$$R_{sc,\,\alpha} = G\sqrt{\frac{1-\eta_\alpha}{\eta_\alpha N_\alpha}}; \quad N_\alpha = \frac{E_\gamma}{\varepsilon_\alpha} \tag{7}$$

where $\eta_\alpha = (\eta_{sc}, \eta)$; ε_{sc} and ε_{el} are mean energy of the scintillation quantum and that of the electron-hole pair formation in the semiconductor, respectively. The total statistical contribution is

$$R_{ST} = \frac{G}{\sqrt{\eta(E_\gamma/\varepsilon_{el})}}\sqrt{1 + K_Y(1 - \eta_{sc}\frac{\varepsilon_{sc} + \varepsilon_{el}}{\varepsilon_{sc}})}\,, \tag{8}$$

where an auxiliary $K_Y = (\eta/\eta_{sc})(\varepsilon_{sc}/\varepsilon_{el})$ is introduced (the effective collection coefficient). As a rule, $\varepsilon_{sc} = hc/\lambda = 1239/\lambda(nm) \approx 2 \div 3\,eV$; $\varepsilon_{el}(Si) = 3.6\,eV$. For detectors with low conversion yield, in the limiting case $\eta \ll \eta_{sc} \ll 1$, the usual Poisson electron noise is obtained from Eq. (8):

$$R_{ST} \approx R^{poisson}_{st,el} = \frac{G}{\sqrt{\eta(E_\gamma/\varepsilon_{el})}}. \tag{9}$$

At $\eta_{sc} > 20\%$ and $\eta > 10\%$, the difference between the binomial distribution and the Poisson one become substantial, the fluctuations of the former drop more sharply than those of the latter. This evidences that it is reasonable to enhance η and η_{sc} for maximum attenuation of the threshold statistical fluctuations. At the ideal energy conversion, $\eta = = \eta_{sc} = 1$, the theoretical limit $R_{st}(\eta = 1) = 0$ is attained. An important peculiarity of the statistical resolution component following from (8) consists in its monotonous dependence on the conversion efficiencies. Other contributions to the total resolutions have been noted above to have not that property.

It is reasonable to transform (8) so that discriminate η_{sc}

$$R_{st} = \frac{G}{\sqrt{\eta_{sc}\,(E_\gamma/\varepsilon_{el})}}\sqrt{K_Y^{-1} + \left(1 - \eta_{sc}\frac{\varepsilon_{sc} + \varepsilon_{el}}{\varepsilon_{sc}}\right)}\,. \tag{10}$$

Solving this equation with respect to η_{sc},

$$\eta_{sc} = \frac{6.91}{E_\gamma(keV)\lambda(nm)}\,\frac{1 + K_Y^{-1}}{\left[R_{ST}^2 + \frac{6.91}{E_\gamma(keV)\lambda(nm)}\frac{\varepsilon_{sc}+\varepsilon_{el}}{\varepsilon_{el}}\right]}\,, \tag{11}$$

we obtain an expression defining the scintillation efficiency necessary to attain a pre-specified level of statistical noise in detector having the efficiency K_Y defining the matching between the scintillator and the photodiode ($0 < K_Y < l$).

When the spectral and optical match is ideal, K_Y depends mainly on the light collection coefficient K_c, so $(\varepsilon_{el}/\varepsilon_{sc})K_Y \sim K_c$. At a good light collection (K_c to 0.8), the statistical resolution of a "red" scintillator ($\lambda = 640nm$) on moderate energy ($E_\gamma = 662keV$) can be believed to be small under condition following from equation (11)

$$R_{ST}(E_\gamma < 1MeV) < 1\% \Leftrightarrow \quad \eta_{sc} \geq 20 \div 30\%\,. \tag{12}$$

This level is $\eta > 10 - 15\%$ for the total conversion efficiency. In high energy range ($E_\gamma > 10MeV$), the statistical resolution drops sharply in a spontaneous way, since $R_{st} \propto 1/\sqrt{E_\gamma}$. The statistical noise on the *662 keV* line is 2 to *4%* in best scintillator assemblies [12]. At $E_\gamma \sim 10MeV$, that contribution will be reduced 3 to 4 times to a value less than *1%* .

To conclude, it is seen that the statistical contribution can be minimized essentially in a detector having a high scintillation efficiency and a good-matched S-PD combination. The first condition is of high necessity to optimize another contribution being in our opinion the most important one, namely, the scintillator intrinsic energy resolution. As a rule, non-statistical (non-Gaussian) fluctuations are included therein. The intrinsic resolution R_{sc} is a natural improvement limit for the total resolution of a detector, since it includes as a rule contributions remaining substantial (or independent of E_γ) at any energies of the ionizing radiation, including high ones. The R_{SC} would be a decisive part in detectors with improved spectrometric resolution $R < 1$ to *2%*).

The scintillator intrinsic resolution was noted to be of importance in the studies of alkali halide scintillators ([3-6] and other works) where it comes as a rule to 4 or 5% . In the case of heavy oxides (BGO and CWO), the intrinsic resolution of rather small samples ($V \sim 1$ to $10\,sm^3$) is negligible due to the proportionality of their light yield [13]. The ZnSe(Te) scintillator intrinsic resolution is $R_{sc} = 3.26\%$ at the S-PD couple resolution

$R = 5.37\%$ on the ^{137}Cs line [14]. The RbGd2Br7:Ce scintillator with proportional light yield seems to exhibit a rather good intrinsic resolution [15]: the total resolution on the same *662 keV* line was $R = 4.1\%$, while the PMT statistical noise being the main contribution in that case was $R_{sc} = 3.5\%$. There are no experimental data on the intrinsic resolution of new scintillators with high values of atomic numbers Z and η_{sc}.

The intrinsic resolution consists of several components. Some of those depend on E_γ, dropping monotonously as a rule. There are, however, components fully or almost independent of the ionizing radiation energy if the latter is absorbed completely in the crystal (the leak resolution or boundary effects being neglected). Among those threshold contributions, it is just the scintillator substance resolution R_{sub} and the light collection non-uniformity one R_{lc} that are the most substantial ones, that is, at an accuracy to small corrections,

$$R_{sc}^2 = R_{sub}^2 + R_{lc}^2 + o(1/\eta_{sc}E_\gamma)\,. \tag{13}$$

The substance resolution R_{sub} depends mainly on the light yield non-proportionality, $E_{sc} = \eta_{sc}(E_\gamma)E_\gamma$, $\eta_{sc} \neq const$. The light collection contribution, R_{lc} , is defined in first turn by the geometric and dynamic fluctuations in a scintillator of a specific shape, the optical parameters in the crystal volume and at its boundary being fixed. The space non-uniformity of scintillations, $\eta_{sc} = \eta_{sc}(\vec{r})$ can be of importance, in particular, in activated compounds.

There are scintillators with very low R_{sub} the light yield proportionality is their specific feature. The tungstates mentioned above belong to those. So, CdWO4 has an R_{sub} about *0.3%* (as discriminated from the total resolution) at the crystal volume $V \sim 200sm^3$ and $R_{sub} \approx 0.03$ to 0.08% at $V \sim 3$ to $20sm^3$ [16]. ZnSe(Te) with nonlinearity factor $\eta(5.9keV)/\eta(662keV) = 85\%$ and $\eta(16.6keV)/\eta(662keV) = 90\%$ has a rather good linearity at the physical light yield $L = 28000ph/MeV$ [10]. Some complex oxides are somewhat worse, e.g., Lu3Al5O12:Ce has the light yield $L = 13000ph/MeV$ and $\eta(16.6keV)/\eta(662keV) = 76\%$ while for LuA1O3:Ce the linearity worsens $\eta(16.6keV)/$ $/\eta(662keV) = 71\%$ as the light yield drops ($L = 11000ph/MeV$) [17]. For comparison sake, the non-linearity of NaJ(TI) is about 80% at a light yield $L = 40000ph/MeV$. Nevertheless, those compounds, as well as other modern scintillators, e.g., those of LSO(Ce) type [18], may turn out to be of promise to attain a high energy resolution of scintillators, including both total and intrinsic one, as their scintillation characteristics will be further improved.

To minimize the substance contribution, a material should be developed having a high scintillation efficiency, homogeneity and, most likely, an intrinsic emission. Since the conversion process in scintillator is a multi-factor process, there is no functional relation between η, and R_{sub} . The above examples show, however, that there is such a correlation for materials of the same type while it is not confirmed when materials of substantially different types are compared. For example, CdWO4 has the light yield 30 % related to CsJ(TI) but their total resolutions are comparable [19] due to that the intrinsic resolution of the former is much lower (2 to 3 decimal orders).

The space uniformity of scintillations should be high enough along with their proportionality ($R_{sub,nonprop} \ll 1\%$). Corresponding residual resolution (as defined in [6])

$$R_{sub,in} = 2.36\frac{\sqrt{<\eta_{sc}^2> - <\eta_{sc}>^2}}{<\eta_{sc}>}; \quad <...> = \frac{1}{V}\int\limits_{V_{sc}} d\vec{r}... \tag{14}$$

is small, $R_{sub,in} < 1\%$, under condition that $(\Delta\eta_{sc}) < 10^{-4}\langle\eta_{sc}\rangle$. That condition will be met in systems where fluctuations are very small, e.g., in a regular lattice. The known method to compensate the η_{sc} non-uniformity in an activated scintillator by providing the light collection non-uniformity (the multiplicative noise of $\langle\eta_{sc}K_c\rangle \neq \langle\eta_{sc}\rangle\langle K_c\rangle$ value) is unsuitable in this case because it results in a definite drop of $\langle K_c\rangle$ and thus of the conversion efficiency that is inadmissible in high-resolution detectors.

Now let geometric fluctuations of light collection, R_{lc}, be considered. At the uniform scintillation distribution R_{lc} is due only to the dispersion of light collection coefficient and, in spite of the non-statistical fluctuation character, has the following form under Gaussian approximation:

$$R_{\,\sigma} = 2.36\frac{\sqrt{< K_c^2 > - < K_c >^2}}{< K_c >}\,. \tag{15}$$

The light collection parameters are expressed via the invariant distribution function ρ for the totality of light beams being reflected from boundary $\partial\Omega$ [20]. The averaged $\langle K_c\rangle$ is

$$< K_c >= 1 - \int\limits_{\Phi_{catch}}\int \rho(\varphi_1,\varphi_2)d\varphi_1 d\varphi_2; \quad \vec{r}(\varphi) \in \partial\Omega\,, \tag{16}$$

where the integration is made over the part of the system phase space Φ_{capt} corresponding to the captured light.

The light collection resolution, as well as the coefficient K_c itself, depends on the scintillator geometry and optical properties (the light reflection, refraction and absorption). When the light collection is ideal, the reflection at the boundary is the mirror one and there is no light absorption in the scintillator, the resolution is minimum, $R_{lc} < 1\%$. Strictly speaking, the theoretical limit $R_{lc} = 0$ is attained in this case, that is confirmed by several authors (see e.g. [16]). The reason for the ideal character of mirror light collection is established within the frame of stochastic (geometry-dynamic) light collection theory [20]. In this case, a dynamic model presenting a billiard with elastic reflections at the boundaries, is considered instead of the detector. There are no fluctuations for mirror light collection, $< K_c >^2 = < K_c >^2$, due to the unique (deterministic) character of the light propagation. Therefore,

$$R_{lc,mirror}(\kappa = 0) \equiv 0\,. \tag{17}$$

(where κ is absorption coefficient). There is a quite different situation when the absorption takes place. It results not only in reduced scintillation intensity but also causes a light collection non-uniformity. The effective light collection with a high resolution is attained in small-size and/or optically transparent scintillators. It follows from experiments, numerical calculations and general considerations that the light collection resolution is small enough ($R_{lc} \ll 1\%$) or a regular geometry scintillator of a volume Vabout $10\,sm^3$ (e.g., for a cylinder with $H \sim D \sim 3sm$) and having mirror-reflecting boundaries (with mirror efficiency $\rho_m \sim 0.8$ or 0.9) under condition that

$$R_{lc} < 1\% \Leftrightarrow \kappa d \leq 0.1 \quad (10d \leq l), \tag{18}$$

where κ is the optical absorption coefficient; $l = \kappa^{-1}$, the light beam free path in the scintillator; d – the crystal characteristic dimension. A good light collection, $K_c \sim 60\%$, is attained under the same conditions.

To conclude, a convenient determination of R_{sc} from the total one, R, measured at several E_γ values is described in what follows. Since $R_{st}^2 = const/E_\gamma$ and the total R is determined from (4), we obtain at known

$$R_{sc} = \sqrt{\frac{R_1^2 E_{1\gamma} - R_2^2 E_{2\gamma}}{E_{1\gamma} - E_{2\gamma}} - R_{PD}^2} \quad , \tag{19}$$

For small-size samples where $R_{lc} \ll 1\%$, $R_{sc} \sim R_{sub}$. The scintillator intrinsic resolution is minimum for detectors spectral line a pronounced Gaussian character of, i.e. $R^2 \sim 1/E_\gamma$.

For medium energies, $E_\gamma < 1MeV$, the energy resolution limit depends on the statistical fluctuation level. To attain R_{st} to 2%, it is necessary to use scintillators with high conversion efficiency ($\eta_{sc} \sim 20\%$) and good matching (both spectral and optical) between S and PD as well as to optimize the light collection coefficient so that the total efficiency η would be not less than 10%.

For the high energy range, $E_\gamma > 10MeV$, it is the intrinsic energy resolution of the scintillator that is decisive. It consists of several components which are in general competing with each other. First of all, scintillators are to be sought having a vanishing resolution of the material independent of the crystal dimensions and being defined by the light yield non-proportionality due to the emission mechanism itself. Moreover, the scintillator size (volume) is to be restricted to minimize non-uniformity in the light collection and in the optical absorption factor. This may result in reduced intrinsic resolution caused by the light yield non-proportionality associated with the ionizing radiation incomplete absorption (leaks) and by increased contribution from microscale inhomogenates (in activated scintillators). The leak resolution can be avoided if radiation weakening of y emission in the scintillator is complete and the secondary electron path length therein is small enough, thus, under conditions (2 to 3) $l_r < d$, where $l_r \sim Z^p$ ($p = 2 \div 5$) is the scintillator radiation length, and $10 l_e < d$, where $l_e \sim 0.45E(MeV)/\rho_{sub}(g/sm^3)$ is the electron free path in the scintillator. A conclusion of importance follows therefrom that the intrinsic R_{sc} will be reduced considerably in scintillators with high Z and η values.

It is of interest to compare experimental data on energy resolution at α, β-particles and γ-radiation recording using a modern scintillator with high conversion efficiency (ZnSe-Te). The energy conversion for β and γ-radiation takes place in essentially the same range (for α in somewhat higher one). The conversion efficiency, however, is close to *100%* for α and β particles while it is less than *1%* for γ-radiation, the scintillator thickness being about $1mm$ in all cases. That is, the complete energy absorption, light conversion optimization and low statistical noise are simulated correctly for α and β particles in a high conversion efficiency scintillator. In contrast, as y radiation is detected, the photoreceiver and electronic noises are of substantial importance due to low conversion efficiency. It is seen (Fig.l) that the experimental result for α and β detection using a S-PD couple coincides essentially with SCD data being several per cent (4 to 6%).

ZnSe has a low transparency, thus, it is unreasonable to use the large crystals for high-efficiency absorption of y radiation. The energy resolution of thin scintillators on *662 keV* line (Fig.l), however, confirms, under account for the predominant part of PD and electronic noises, the attainability of a high energy resolution using an S-PD combination

using a homogeneous scintilla-tor transparent against intrinsic emission and showing a high conversion efficiency as well as a low intrinsic resolution. To compare (see Fig. 2), the energy resolution for standard CsJ(Tl) is less than *6%* on *662 keV* line and less than *5%* on *1.33 MeV* one at room temperature.

In high energy range, $E_\gamma > 10MeV$, all requirements concerning the medium energy range remain valid. Under account for the obligatory high detector efficiency, i.e., the high-energy radiation absorption coefficient of several tens per cent, it is just high intrinsic resolution, homogeneity and light collection optimization that become the decisive factors. The resolution reduction down to *1%* and less is illustrated (Fig. 3) for lead tungstate detectors (GeV energy range). In practice, this means that non-activated scintillators of high Z and small radiation length should be used having the emission in "red" spectral range providing a better matching with the photodiode. Note that in the high energy range the same absorption efficiency is attained at the BGO or PWO scintillator volume 8 times smaller than that of CsJ or NaJ. The improvement of the conversion efficiency for high atomic number scintillators is here the main problem.

The theoretical analysis allows to conclude that it is quite possible physically to attain sufficiently low values of R_{PD}, R_{ST} and R_{SC} components of S-PD detector energy resolution (except for low-energy range where the statistical contribution predominates and increases sharply as the radiation energy drops). Thus, it is possible to attain $R = 1\%$ to 2% . The necessary conditions for such a small spectral line broadening (as compared to existing scintielectron detectors having $R = 4$ to 5%) are a considerably improved conversion efficiency (by a factor 1.5 to 2) and scintillation one (by a factor of 2 to 3, i.e., up to $\eta_{sc} \sim 25 - 30\%$). It is necessary also to search for optically transparent homogeneous scintillators close to intrinsic emission exhibiting a low non-proportionality of light yield (small intrinsic resolution) and high atomic number.

The modern advances in production of high Z crystals exceeding CsJ(TI) in light yield [21,22] evidence the practical solvability of that task.

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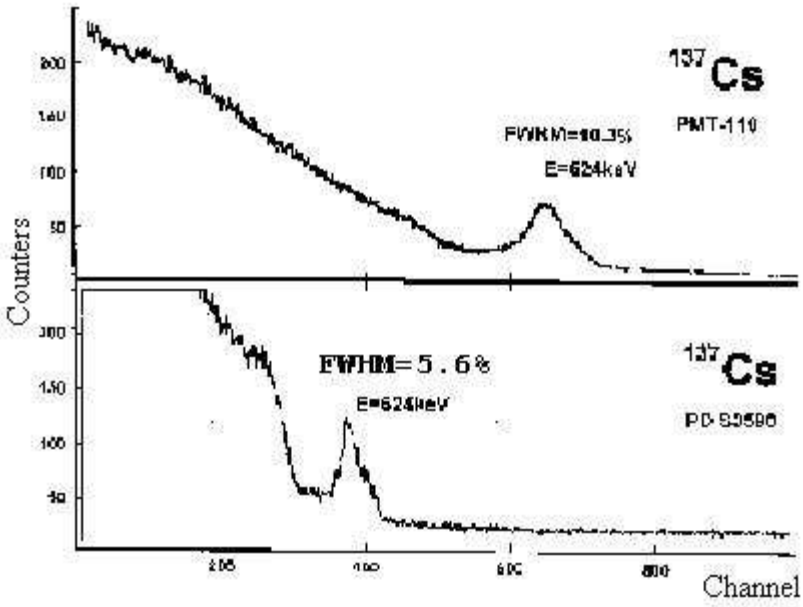

Fig. 1. Spectrum of ^{137}Cs conversion electrons recorded by an S-PMT couple (a) and an S-PD one (b). Scintillator ZnSe(Te), $1mm$ thick.

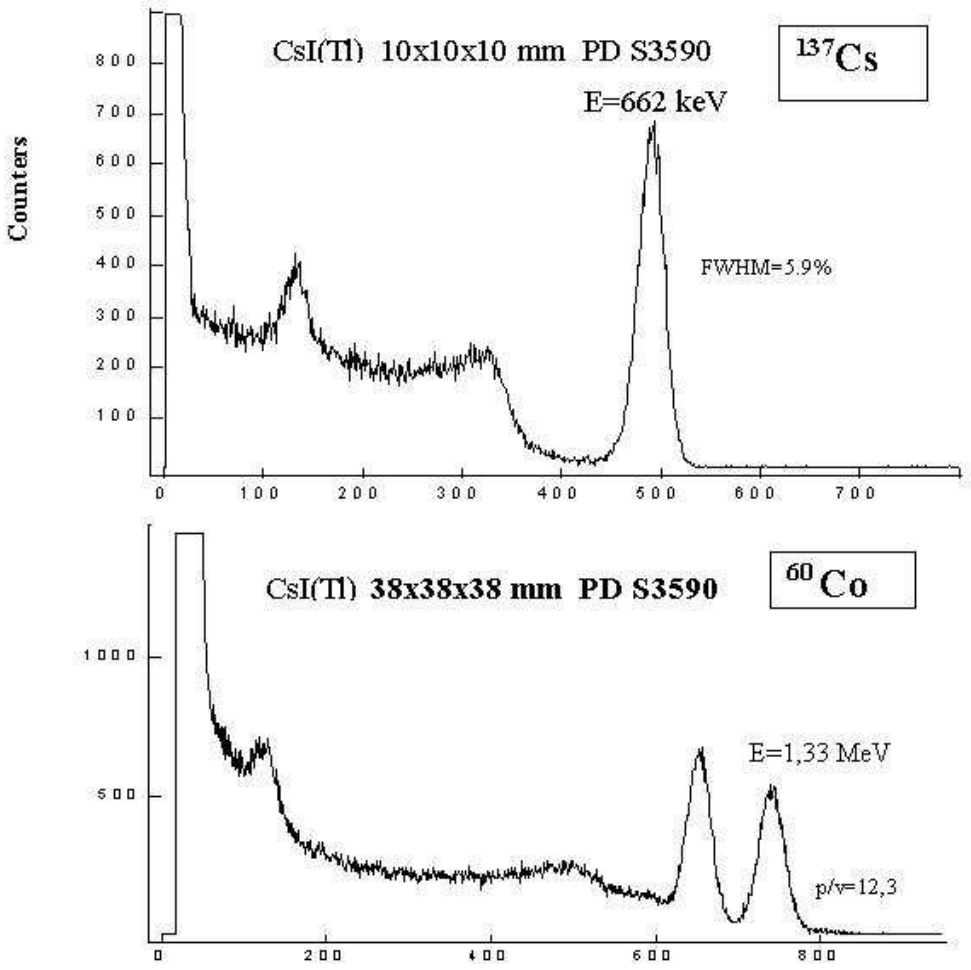

Fig. 2. ^{137}Cs (a) and ^{60}Co (b) radiation spectra detected S-PD (CsJ(TI) and PD S3590); scintillator size: a) 10x10x10mm^3, b) 38x38x38mm^3.

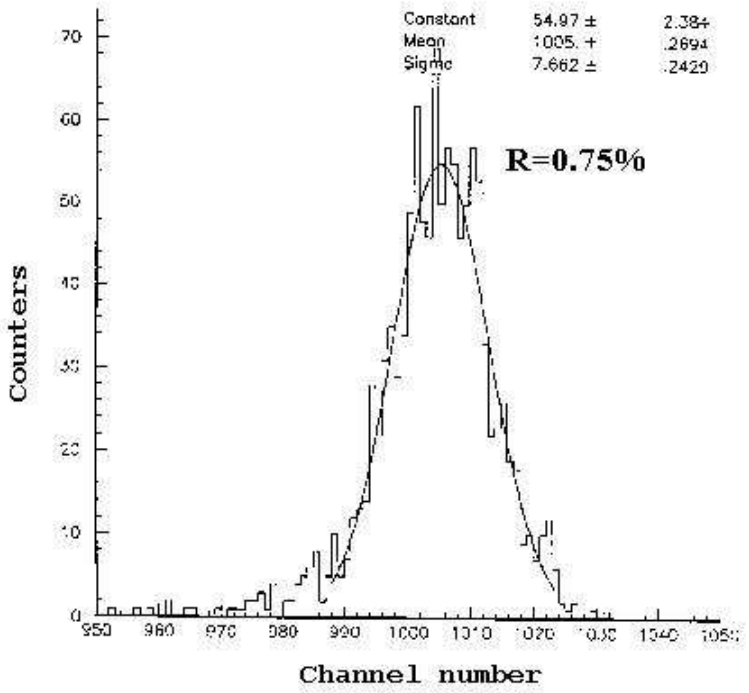

Fig. 3. $100GeV$ radiation spectra detected by S-PD assembly with a PbWO4 scintillator and PD S3590 potodiode. Resolution less than 0.75% in both cases.